MEASURING INFORMATION GAIN IN THE OBJECTIVE FORCE

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26 September 2003

ABSTRACT

As the Army enters its transformation, many are attempting to quantify or understand the value of information on the battlefield. Information can be decomposed into various qualities. In this paper we focus on three components of information—timeliness, accuracy, and completeness. We describe a simulation framework that allows us to separately vary these three information components. Our basic scenario is a typical vignette of an Objective Force company-sized element conducting offensive operations against threat elements. Knowledge of the threat is compromised by the presence of decoy elements as well as previously damaged or killed systems. In this scenario the fires are initiated from standoff ranges. The initial and running assessments of the threat composition are made based on the information provided by sensors on board the unit's organic unmanned aerial vehicles.

Our results show that the three components of information quality play distinct roles in affecting the overall effectiveness of the force as reflected in an efficiency measure. Additionally, critical thresholds for accuracy, completeness, and timeliness of information are pinpointed to inform Objective Force decision makers.

INTRODUCTION

The U.S. Army's new Objective Force design calls for a new paradigm in fighting our future battles. Objective Force units are anticipated to have the capability to "see first, understand first, act first and finish decisively" (TRADOC). The key to making this concept a reality is an overwhelming situational understanding largely made possible by the ability to obtain, process and rapidly move an abundance of information on the future battlefield.

The traditional elements of combat power include maneuver, firepower, protection and leadership. According to Army concept developers, however, it is envisioned that in Objective Force units a "situational understanding derived from real-time, accurate Information raises combat power exponentially" (U.S. Army Training and Doctrine Command 2002). One example of the impact of information, consistent with the idea expressed in the above formula, is a recent observation by VADM(ret.) Cebrowski (2003): "The air force says that a target once requiring 1,000 bombs to destroy now requires only one. That magnitude of change is owed almost entirely to information technology and processes."

There is currently great emphasis on the merits of information, and much effort is going into how it can be obtained more quickly, completely and accurately. However, "little has been done to establish a clear relationship between information and the outcome of military operations" (Darilek et al. 2001) The first step in attempting to discern this relationship is defining what is meant by the term *information*.

According to Perry (2000), information has two main attributes: *value* and *quality*. Information has *value* if it informs the commander and answers questions posed by his intelligence requirements (such as Priority Intelligence Requirements or Commanders Critical Information Requirements). In other words, valuable information is relevant to the situation at hand. The *quality* of information, however, depends on its accuracy, timeliness and completeness (Alberts et al. 1999, Perry 2000). Timeliness reflects the relationship between the age of an information item and the tasks or missions it must support. Accuracy measures how faithfully the information items represent the realities they describe. Completeness reflects the degree to which all relevant items of information are available, including entities, attributes and the relationships between them.

It is worth noting that valuable information may not always be of high quality. On the other hand, information can be of high quality but have no relevance to the situation at hand, and therefore have little or no value.

In this paper we investigate the impact of information on Objective Force operations. The focus is information quality, as defined by Perry above, and our goal is to present some broad conclusions about how the individual components of information quality can influence combat outcomes. We do this via a simulation of the performance of a Mounted Combat System (MCS) Company Killing Machine under varying components of the quality of information. We describe our model in the next section, and then present the experimental design used to explore its behavior. We discuss the results, and provide general conclusions as well as suggesting some topics that merit further investigation.

SCENARIO

Under the Objective Force concept, the unit of action takes on a role similar to that of the traditional maneuver brigade. There are many critical tasks that must be done with a high level of precision by the unit of action, such as firing and maneuvering under contact, delivering fires at standoff, and assuring mobility near the objective. An additional critical task is tracking and evaluating battle damage assessment. Accurate battle damage assessment facilitates at least two things: (1) decisive action by the commander so he knows when he can transition to subsequent actions and maintain pressure on the enemy, and (2) efficient expenditure of limited munitions (USA TRADOC 2002).

A Mounted Combat System (MCS) Company, one of the unit of action sub-elements, is the subject of our investigation. It is optimized for extended line of sight with beyond line of sight fires, and employs chemical energy and kinetic energy munitions to engage at standoff (USA TRADOC 2002). Its mission in our scenario is to identify and eliminate targets dispersed throughout an objective area using organic fires at standoff ranges. As Figure 1 illustrates, the MCS Company has a total of 10 MCS weapon platforms available to engage targets. It also has three unmanned aerial vehicles (UAVs) that are used to provide the battle damage assessment and target location data.

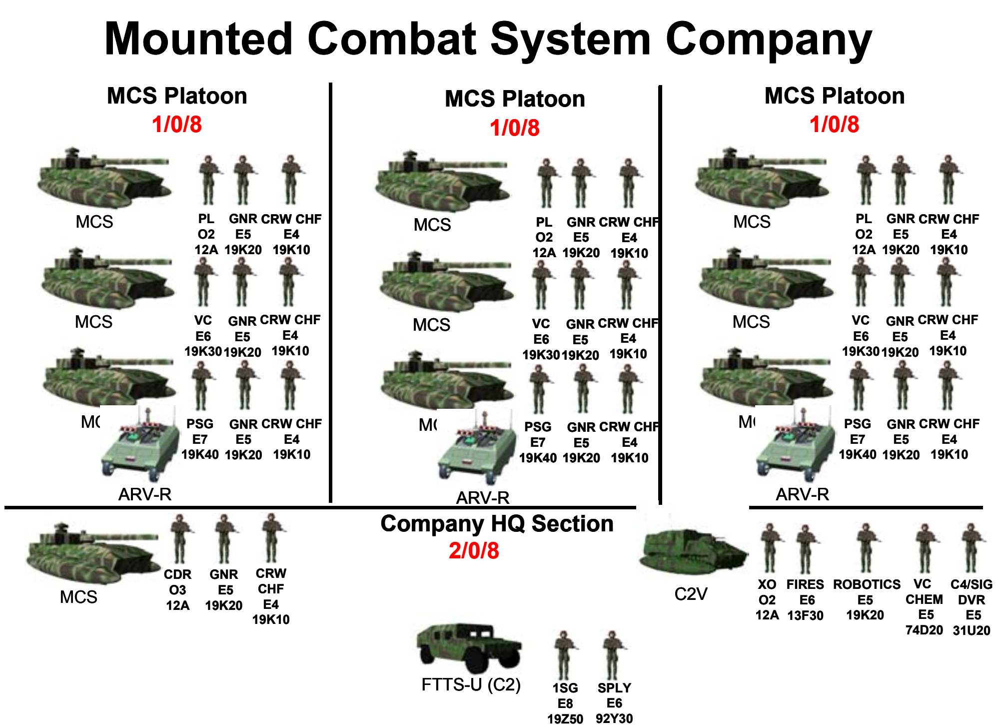


Figure 1: Mounted Combat System Company Equipment

The objective area is an 8-kilometer by 8-kilometer box of primarily open, rolling terrain. The MCS Company is located in an attack by fire (ABF) position and, with stand-off range firing capability, destroys targets in the target area of interest (TAI) in support of a follow-on assault by an adjacent infantry company to take Objective A.

Targets are randomly and uniformly dispersed throughout the objective area. There are 50 total targets and they are broken down into three types with the following distribution: 36 live, 7 dead and 7 decoy. Half of the live targets are specified as movers and will move randomly until killed by munitions fired from an MCS weapon platform. The stationary targets represent systems conducting a static defense, command posts, air defense assets or other fixed sites. Dead targets are systems that are previously damaged or killed. Decoys are non-moving entities that have no military significance but can be mistaken for valid, live targets.

Three UAVs fly in a random pattern and report perceived target imagery to the analysts in the command post. This target imagery serves as the sole basis for target location and target type. With this information a decision will be made to fire or not fire at a target. There are no other reconnaissance assets in the objective area except the UAVs. If a target is perceived as live then a decision to fire at that target is made. The end state is achieved when 80% of the live targets are destroyed. A graphical depiction of the scenario is shown in Figure 2.

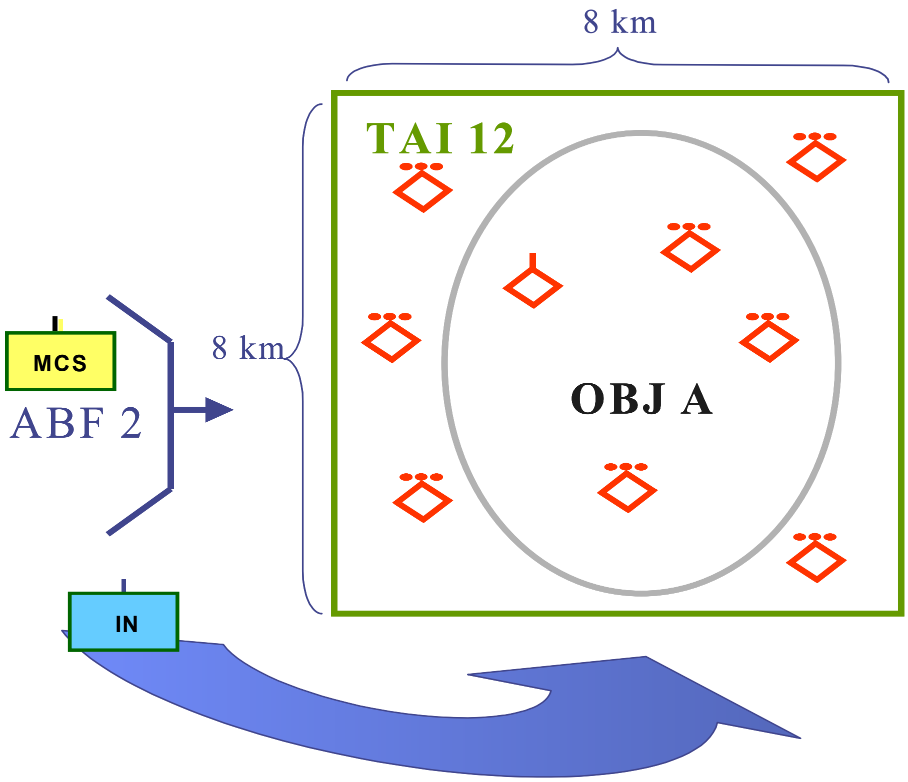


Figure 2: Scenario Environment

In this scenario, the timeliness factor represents the amount of time it takes from the detection of a target to the impact of a round on the target. The imbedded processes are the UAV data transmission time, man/machine image processing time, firing decision time and the round time of flight. Essentially this is the time it takes for raw data to become actionable information combined with the time to complete the resulting action. Accuracy is represented by the conditional probability of classification given that one of the three battlefield entities is present. This is the probability that a live target, dead target or decoy will be classified as such given that it was detected. For the sake of simplicity we assume that if an entity is present in the area being searched it will be detected with a probability of 1.0. Therefore, accuracy is purely a function of the quality of the classification process. Finally, the amount of area on the ground a UAV can observe and evaluate in a given unit of time represents the completeness of information.

MODEL IMPLEMENTATION

For this paper, we developed a discrete-event simulation model called the Mounted Combat System Killing Machine (MCSKM) that treats battle damage assessment, target type and target location as the types of information under observation. MCSKM is written in the JAVA programming language and makes use of the Simkit simulation package (Buss, 2003). With a focus on efficient expenditure of munitions, the model provides a framework for exploring the impact of this information quality components on the results of the scenario described above.

The MCSKM is comprised of two basic processes: a UAV process and a shooting process. In general, a UAV process is instantiated for each UAV represented in the model. In this model there are three UAV processes in place. While each UAV process controls the UAV movement, the shooting process does all of the real work in the model. The shooting process manages all target movements, target classifications, target state changes, firing delays and kill adjudications.

Initializing Targets

At the beginning of each run of the MCSKM, all targets are given an exact grid location based on the 8 kilometers by 8 kilometers objective area. These locations are random, uniformly distributed and given in terms of meters. For example, the lower left corner of the objective area would be grid location (0.0, 0.0) and a target that is 5 kilometers to the right of the origin and 3 kilometers up would be at grid location (5000, 3000). For the 50% of the live targets that are designated as movers, they are assigned an initial random azimuth [0, 2π] to begin movement as well. The movement speed and movement duration can be specified by the user.

UAV Process

The UAV locations are implemented differently. For modeling convenience, the area the UAV can see in a single glimpse is represented as a box. Based on the box size, the objective area is divided up into grids of the same dimension. For example, if the box size is 400 meters x 400 meters for a given run, then the objective area is divided into a 20 by 20 grid system (8000m/400m = 20, the number of grids on each axis). Each UAV has a random starting location in one of these grids for each run of the MCSKM. Figure 3 demonstrates starting locations of (5, 5), (10, 15) and (18, 10) for the three UAVS.

Movement of a single UAV is simulated by “looking” at one particular grid square for the amount of time it would take the UAV to move the width of the grid square in a linear fashion at a fixed speed. For example, using a UAV speed of 120 km/h, if the grid square is 400m x 400m then the time in grid = (400m)/(120 km/h) = 12 seconds. The choice to move from one grid square to another instead of tracing out a precise path along exact coordinates was made for the sake of simplicity in programming. To travel 400 meters in 12 seconds with a sensor sweep width of 400 meters is roughly equivalent to occupying a 400m x 400m grid square for 12 seconds. Although some precision is lost in the case of a diagonal move, it is not of great concern in light of the fact that the UAV movement is already abstracted.

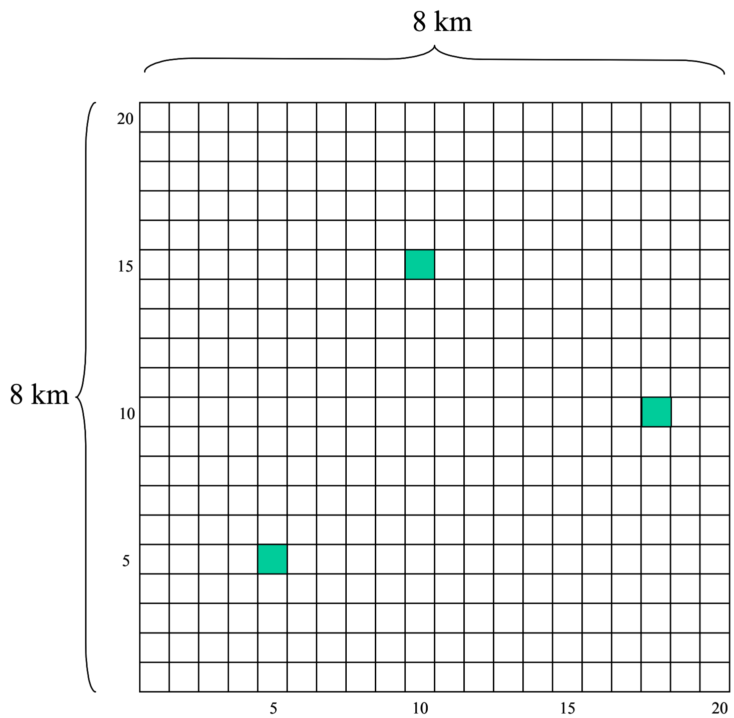
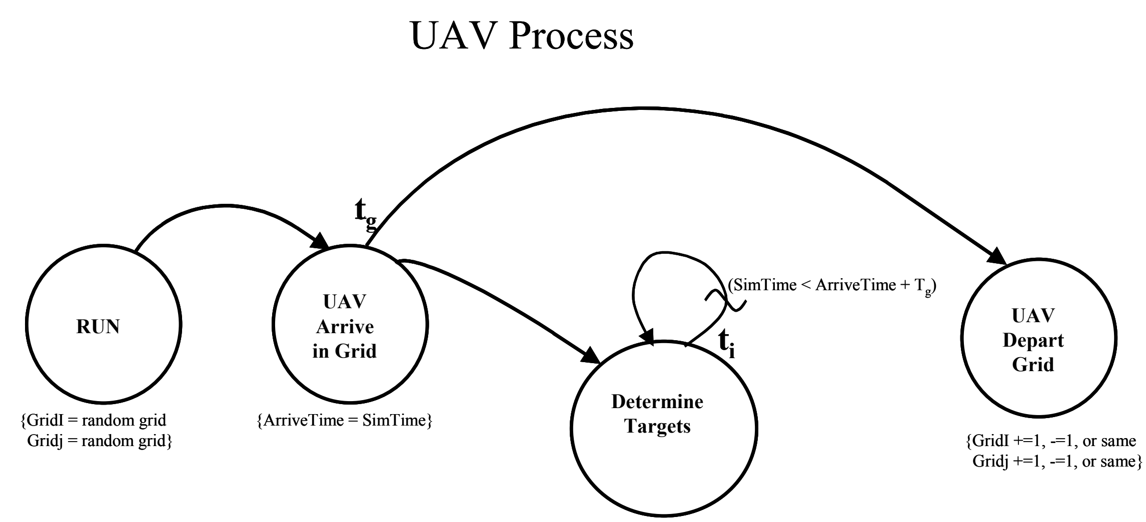


Figure 3: UAV Starting Locations in the Target Area of Interest

After this time has passed, the UAV "moves" to an adjacent grid square in a random manner. The UAV can move into any one of the eight adjacent grid squares but it cannot remain stationary. If the UAV is on the border of the objective area, it is not allowed to move in any direction that would take it outside the objective area. The footprint of what the UAV can see (have the potential to detect and classify) on the ground is represented by the size of the grid square. This is the part of the model where completeness plays its role. The size of the grid square, in conjunction with the speed of the UAV, controls the amount of information available per period of time.



<u>Parameters</u>

t_g – time in grid

t_i – time between glimpses

<u>State Variables</u>

gridI – grid number in X orientation

gridJ – grid number in Y orientation

arriveTime – time of arrival in grid

Figure 4: UAV Process Event Graph

Figure 4 is an *event graph* of the UAV Process. The circles represent events in the simulation, while the arrows depict how events schedule other events. The "RUN" event initializes the UAV in a random starting location and schedules the first arrival in a grid square. Upon arrival, the "UAV Depart Grid" is scheduled for when the time in the grid will have elapsed and a "Determine Targets" is scheduled immediately, which is the UAV's first attempt to detect and classify any targets present. The UAV process merely signals for the "Determine Targets" event to happen; the actual work of this event is done in the shooting process and will be explained shortly. After arriving in the grid and taking an initial glimpse, the UAV will continue to attempt to determine targets by taking glimpses at 5-second intervals until its time in the grid has expired. Once the time is up it will move to another grid in the manner explained above.

Shooting Process

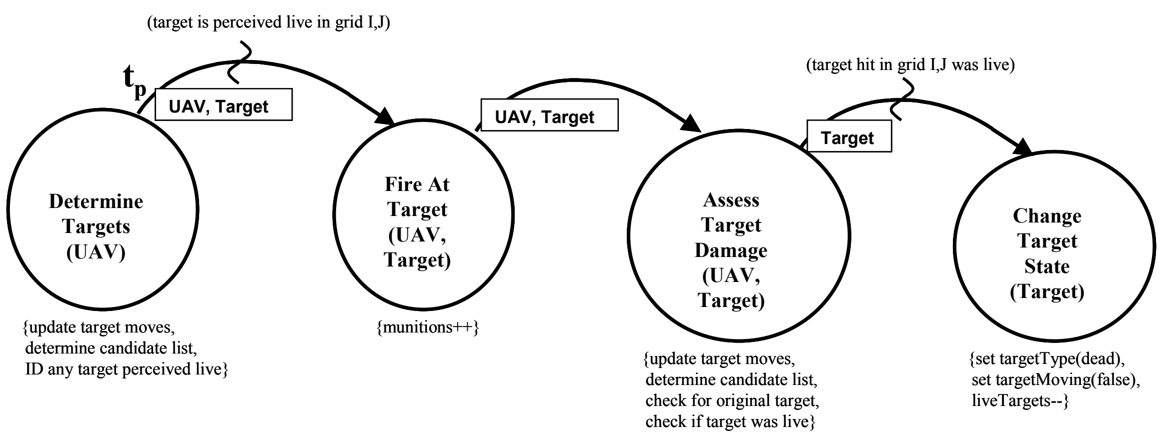
The shooting process is initiated by any UAV Process's call for a "Determine Targets" event. The model contains variables for the probability of false detection (type II error), the probability of detection, and the conditional classification probabilities given a detection. However, the probability of false detection was fixed at 0.0 and the probability of detection was fixed at 1.0 for the sake of simplicity in this implementation of the MCSKM. Therefore, if a target is present it will be detected. Once detection occurs, the UAV will classify the target based on the appropriate conditional probability of classification. If a target is detected and classified as live, then a decision to fire is made.

The impact of the round will be delayed by a number of seconds based on the processing time parameter. This simulates the time it takes for raw data to become actionable information and then be acted upon. Once a target is identified as live and has a round fired at it, that target is not eligible for detection again until that round has impacted. This prevents multiple rounds being fired at the same live target in a single grid square. Since half of the live targets are moving, there is always a chance that the original target may not be in the same grid when the round makes impact.

This process iterates until a user-specified target attrition level is achieved, and then the simulation terminates. The implications of changing this threshold are discussed later in this paper. The measure of effectiveness for a given run is the number of munitions required to reach the specified level of attrition.

Figure 5 is an event graph of the Shooting Process. Since this is where the bulk of the simulation takes place, each event will be discussed in detail.

Shooting Process



Parameters	State Variables
t_p – time to process data	munitions – number of MCS munitions fired
p_c – p(perceived|actual)	liveTargets – number of live targets remaining

Figure 5: Shooting Process Event Graph

"Determine Targets" Event

The "Determine Targets" event in the Shooting Process is scheduled by the "Determine Targets" event in the UAV Process. The Shooting Process knows when to conduct this event because it "listens" to the UAV Processes. The UAV Process passes in its grid location so that the Shooting Process knows where to look for targets.

Since some of the live targets are movers, their locations are updated first. Moving targets move at a fixed speed for a fixed duration in a linear fashion before they stop and change direction. The speed and move duration are both variable but in this analysis they are held constant at 27 km/h and 80 seconds respectively. At the end of a target's move, a new azimuth is randomly generated and the target commences its movement. Azimuths that will lead a target out of the objective area by the end of its move segment are not allowed.

Once target location adjustments are made for the movers, the list of Target objects is iterated through to determine which targets are in the current grid of interest. Targets that are located in the grid are pulled from the master target list and added to a separate candidate list. Each target on the candidate list is then classified as either live, dead or a decoy based on the conditional probability of classification.

This is the part of the model where accuracy plays its role. The conditional classification probabilities directly affect the quality of target information. For example, if p(target is perceived live | target is actually dead) = .2, then there is a 20% chance that a dead target will be misclassified as live. Targets that are classified as dead or decoy are returned to the master target list. However, any target that is classified as live is sent to the "Fire At Target" event, along with the location of the UAV when this target was detected and classified.

Once a target is perceived (or classified) as live it does not go back into the master target list until later in the process. This is so because the same UAV will make multiple glimpses in the same grid before it moves to the next grid. If it has the opportunity to reclassify the same target again as live on a subsequent glimpse, then another round of munitions gets called in on the same target and the overall number of rounds to kill the targets at the end of the simulation becomes abnormally high. When the "Determine Targets" event iterates through the master target list, the target just identified as live and having a round designated for it will not again be available for detection and classification until the round has impacted.

"Fire At Target" Event

The "Fire At Target" event is simple, but symbolically very important. This is the part of the model where timeliness plays its role. Firing does not take place immediately on detection, but rather after the aggregated total processing time has elapsed. Since some of the live targets are movers, the target that originally prompted the firing of a round may not be in the grid when the round makes impact.

The parameters passed in from the "Determine Targets" event, the target and UAV location, are simply carried along and passed on to the next event. The "Fire At Target" event does not do anything with these parameters. The purpose of this event is to record the expenditure of a munition and immediately schedule an "Assess Target Damage" event. Technically there would be a time of flight for the round that would take place after the firing event. However, that time is accounted for as one of the components of the aggregated total processing time leading up to the "Fire At Target" event. Therefore the "Assess Target Damage" event is immediately scheduled with a delay of 0.0 seconds.

"Assess Target Damage" Event

At this point the round that was scheduled to be fired (when a target was perceived live back in the "Determine Targets" event) is now about to make impact. The target that was passed in to this event as a parameter from the "Fire At Target" event is now placed back in the master target list.

As in the "Determine Targets" event, moving target locations must be updated. This happens right before the strike of the round and right after the target triggering the fire is placed back in the master target list. This gives the target that has been held out of the list a chance to update its location before the round selects a target.

The UAV parameter that gets passed in to this event contains the grid location of the UAV when the original target was detected and classified. The target list is iterated through and a new candidate list is built consisting of targets that are currently located in the grid. The candidate list is then iterated through in order to find the original target. If the original target is found, then the round hits that target. If the original target is not found, but there are other targets in the candidate list, then a target is randomly chosen from the list to be hit by the round. Once a target is taken from the candidate list to be hit by the round, all other targets are returned to the master target list. If no targets are in the candidate list, then the round becomes wasted. If the target chosen by the round is actually already dead or a decoy, even though it was perceived live, that target is simply returned to the master target list and available for detection again. If the target chosen by the round is actually live, then that target is passed as a parameter to the "Change Target State" event with a delay of 0.0 seconds.

There are a few important notes regarding the accuracy of the munitions. As depicted in Figure 6, it is envisioned that Objective Force units conducting beyond-line-of-sight fire missions will be utilizing extended-range precision-guided munitions effective out to 12 kilometers (Andrews 2001). Because the MCS Company in the simulation model is conducting fire missions at maximum ranges from 8-12 kilometers, when a round is fired into a grid it will kill any target in that grid with a probability of 1.0. This seems consistent with the technical vision for beyond-line-of-sight munitions capability in the Objective Force.

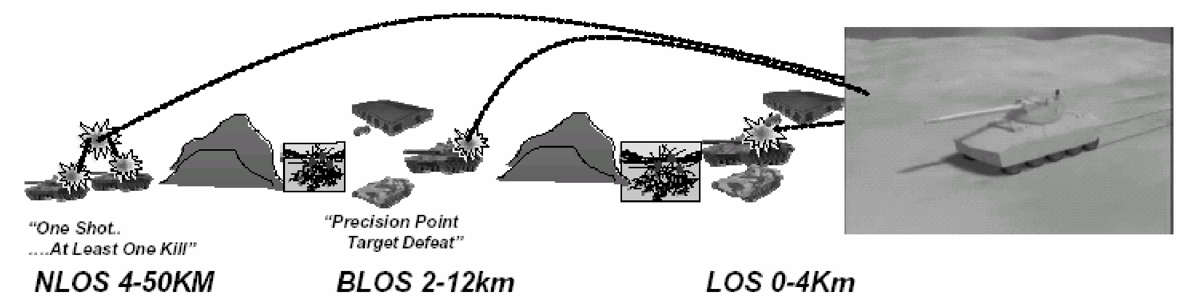


Figure 6: Objective Force Fire Missions

Measure of Effectiveness Explanation

When it comes to resource allocation, there is a tension between effectiveness and efficiency (U. S. Army, 2001). The mission must get accomplished so effectiveness is of primary importance. However, if there are multiple ways of accomplishing the mission the most efficient one with regards to expenditure of resources is preferred.

By design, the MCSKM will eventually accomplish the mission. Since all targets are at standoff ranges there is no threat of return fire. Given sufficient time, the MCS Company will eventually get the enemy down to the desired attrition level regardless of the information quality. Therefore, the question becomes one of efficiency. That is why our chosen measure of effectiveness to determine the relative importance of information timeliness, accuracy and completeness is the number of munitions fired.

Modeling Issues

Before running the final experiment, we spent time exercising the model over many different parameter configurations—including some that we ended up setting at fixed levels. One insight gained from this trial-and-error approach was that some small performance errors were magnified by the MCSKM. This occurs for several reasons. First, since the UAV can make a detection at every glimpse, in the course of an entire run of a scenario there are so many glimpses that even if the probability of false detection is as small as .01 there could be hundreds of false detections each resulting in a wasted round. The probability of detection compounded this problem by dragging out the simulation. If a target was present in the grid but not detected, the UAV would pass over it and have to randomly come back to it at a later time. By the time the UAV comes back to the target it has had numerous opportunities to make false detections, misclassify dead or decoy targets as live, and waste more rounds.

The attrition level was yet another contributor to the problem. After the majority of the live targets are found and killed, the UAV has to keep looking for the last few live targets and spends a lot of time wasting rounds in the meantime. The scenario chosen for this analysis suggested the use of an 80% attrition level (a common benchmark for many aspects of the Objective Force concept) as the stopping criteria. Our preliminary exploration verified that this allows the simulation to run in a reasonable amount of time (which is important for multiple runs).

Care also had to be taken in modeling completeness, which describes the level to which all relevant items of information are available. Initially this component of information was modeled strictly by the size of the grid square representing the footprint of the UAV's sensor. However, the results did not make much intuitive sense. It became apparent that a UAV could look at four 100m by 100m grid squares in the same amount of time it could look at one 200m by 200m grid square. This happened because the UAV traveled at a fixed speed and the time in the grid square was adjusted at each completeness level to account for this. In other words, for any given block of time the same amount of area on the ground was potentially covered regardless of the completeness setting. Since target information was the relevant item in this scenario, the piece of information that contained data on the most number of targets was the most complete. To model completeness more appropriately, the levels were redefined so that time in the grid square was held fixed and the size of the grid square changed. This required UAV speed (which was previously held constant) to vary in conjunction with the grid size.

Further details of these (and other) modeling issues are described in Baird (2003). They underscore the importance of checking the modeling logic to insure that the results will be meaningful, as well as the potential benefits of using a simple vs. highly detailed model. According to Law and Kelton (2001), an indicator that a simulation is working properly is that is produces reasonable output when run under a variety of settings of the input parameters. The performance error magnifications described above might not, in the end, provide qualitatively different assessments of the impact of information components, but by increasing the simulation run lengths they could substantially increase the total time required to make the assessments.

EXPERIMENTAL DESIGN

Because the accuracy, timeliness and completeness component levels each depend on several different parameters in the MCSKM model, we chose to specify combinations that correspond to poor, middle, and good settings for each component. We conducted preliminary investigations with various parameter settings to determine the right mix for the final experiment. Table 1 provides the parameter settings for our final experiment. As mentioned earlier, we held the detection probability at 1.0 and the probability of a false detection at 0.0 so accuracy affects the number of munitions expended only via the correct or incorrect classification of targets as live, dead, or decoy. The actual timeliness levels used in the model are random draws from normal distributions with the means and standard deviations as shown in Table 1. The completeness is represented by differing grid sizes, representing the area observable by UAVs flying at differing speeds.

We remark that MCSKM is flexible enough to allow analysts to vary many parameters we held fixed, such as the number of UAVs, the detection/false detection probabilities, and the UAV transmission intervals. Our purpose with this experiment is not to come up with a detailed model of exactly how the physical system behaves, but rather to capture the essential elements of the scenario in order to draw some insights into the relative impact of the three information quality components.

Table 1: MCSKM Parameter Levels Used in the Experiment

		Scenario Settings		
		Low	Medium	High
Accuracy				
Detection Probability	p(detect | target)	1.0	1.0	1.0
False Detection Probability	p(detect | no target)	0.0	0.0	0.0
Classification Probabilities:	p(live | live)	0.4	0.6	0.8
P(perceived | actual)	p(dead | live)	0.3	0.2	0.1
	p(decoy | live)	0.3	0.2	0.1
	p(live | dead)	0.3	0.2	0.1
	p(dead | dead)	0.4	0.6	0.8
	p(decoy | dead)	0.3	0.2	0.1
	p(live | decoy)	0.3	0.2	0.1
	p(dead | decoy)	0.3	0.2	0.1
	p(decoy | decoy)	0.6	0.6	0.8
Timeliness				
Processing Time Mean	seconds	60	30	10
Processing Time Std. Dev.	seconds	6	3	1
UAV Transmission Interval	seconds	5	5	5
Completeness				
Number of UAVs		3	3	3
Grid Size	meters	100	200	400
UAV speed	km/hr	30	60	120

The individual parameters were changed in groups, as opposed to individually, based on the descriptions of the three levels of the main factors. Each design point represents a unique combination of factor settings. The response at each design point is the average (based on 100 replications) number of munitions fired from the entire collection of MCS weapon platforms to kill 80% of the live targets (the attrition level requested by our sponsor). We used a 3^3 factorial design to specify the design points, meaning there are 3 factors under observation each at three levels (Montgomery 1984). The three factors are timeliness, accuracy and completeness. The three levels correspond to low, middle, and high settings. With three factors at three levels each, there are a total of 27 design points.

RESULTS AND DISCUSSION

The factor settings and mean number of munitions expended are shown in Table 2. We coded the factor values according to the level setting (1=high, 0=medium, -1=low) instead of the actual value used in the simulation in order to facilitate comparisons across the three information components. At a glance, the results seem to meet some common sense expectations. The best (lowest) MOE of 71.23 munitions is realized when timeliness, accuracy and completeness are each set to their highest level. Likewise, when timeliness, accuracy and completeness are each set to their lowest levels they produce nearly the worst MOE of 346.58 munitions. When we evaluate the average munitions expended for one factor at a time, we also find that the MOE improves as the information quality increases. The MOE improves by 80 rounds as timeliness increases from its low to high level, by 105 rounds as accuracy increases, and 123 as completeness increases.

Table 2: Experiment Summary with Means

Design Point	Parameter Settings: Completeness	Accuracy	Timeliness	Munitions
1	1	1	1	71.23
2	1	1	0	81.33
3	1	1	-1	99.92
4	1	0	1	106.38
5	1	0	0	112.72
6	1	0	-1	133.88
7	1	-1	1	143.23
8	1	-1	0	156.94
9	1	-1	-1	170.57
10	0	1	1	81.60
11	0	1	0	137.01
12	0	1	-1	142.16
13	0	0	1	121.23
14	0	0	0	188.77
15	0	0	-1	204.82
16	0	-1	1	161.13
17	0	-1	0	251.80
18	0	-1	-1	248.87
19	-1	1	1	104.42
20	-1	1	0	209.87
21	-1	1	-1	201.38
22	-1	0	1	154.83
23	-1	0	0	279.99
24	-1	0	-1	284.39
25	-1	-1	1	214.07
26	-1	-1	0	382.96
27	-1	-1	-1	368.58

There is ample evidence to suggest that the MCSKM works properly. As well as checking that the model performance conformed to basic expectations, we conducted a detailed trace on the execution of the model was by stepping through the MCSKM event by event. All locations were plotted by hand and state variables were tracked externally to the simulation. Finally, subject matter experts at TRAC-Monterey concurred with the results and agreed they were consistent with the chosen parameter settings.

Since our model has produced some meaningful output, our task becomes one of determining the significance of the information quality components. How important is each factor and by how much does each factor influence the number of munitions fired? In order to address these questions, we fit a complete second order regression model to the data (Table 3). Checking for two-way interactions allows us to gain insight about any synergistic or redundant effects between factors. The squared terms allow us to check for non-linear behavior, such as increasing or diminishing returns for information gain.

Table 3: Polynomial Regression Model of MCSKM Response

	Coefficient	Std. Error	t Statistic	p-value
Intercept	192.34	2.39	80.58	0.00
Completeness	-61.24	1.10	-55.43	0.00
Accuracy	-52.62	1.10	-47.63	0.00
Timeliness	-37.47	1.10	-33.91	0.00
Completeness^2	10.00	1.91	5.22	0.00
Accuracy^2	1.73	1.91	0.90	0.37
Timeliness^2	-34.01	1.91	-17.77	0.00
Completeness:Accuracy	17.47	1.35	12.91	0.00
Completeness:Timeliness	22.96	1.35	16.97	0.00
Accuracy:Timeliness	5.12	1.35	3.78	0.00

The intercept represents the predicted response when all levels are at their medium level (0). The other terms in the model come into play when the level of a factor changes to high (+1) or low (-1). With $R^2 = 0.731$, this regression model accounts for a significant amount of the variation in the MCSKM output data. Figures 7 and 8 depict the relationship between the regression model predictions and the average actual simulation responses, as well as demonstrate the constant variance in the residuals. From Figure 8, note that with the exception of one potential outlier (corresponding to design point 26) the model appears to do a reasonable job of predicting the required munitions.

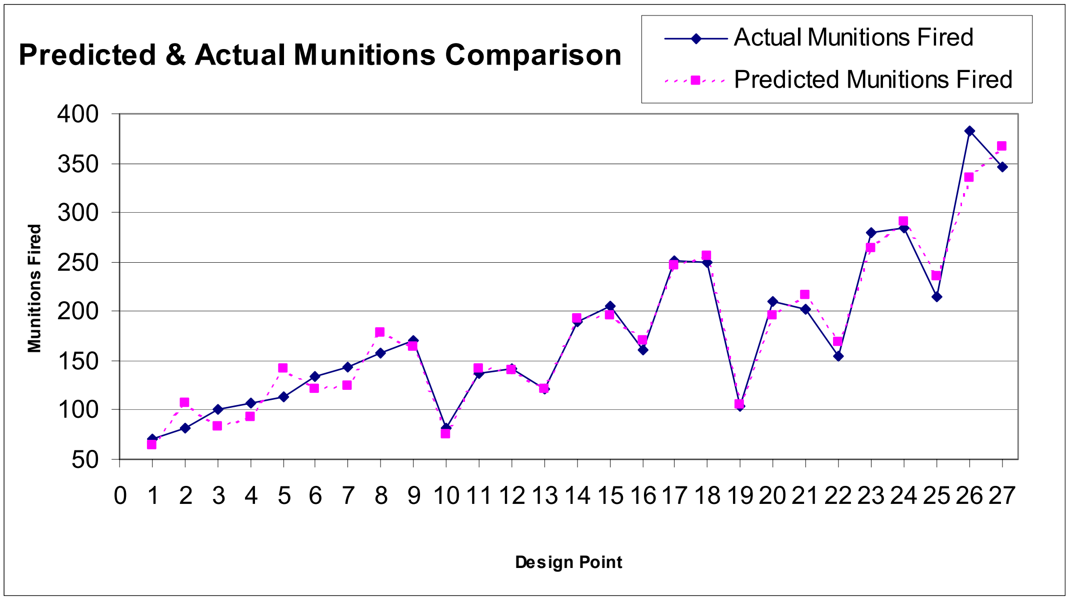


Figure 7: Predicted & Actual Munitions Comparison

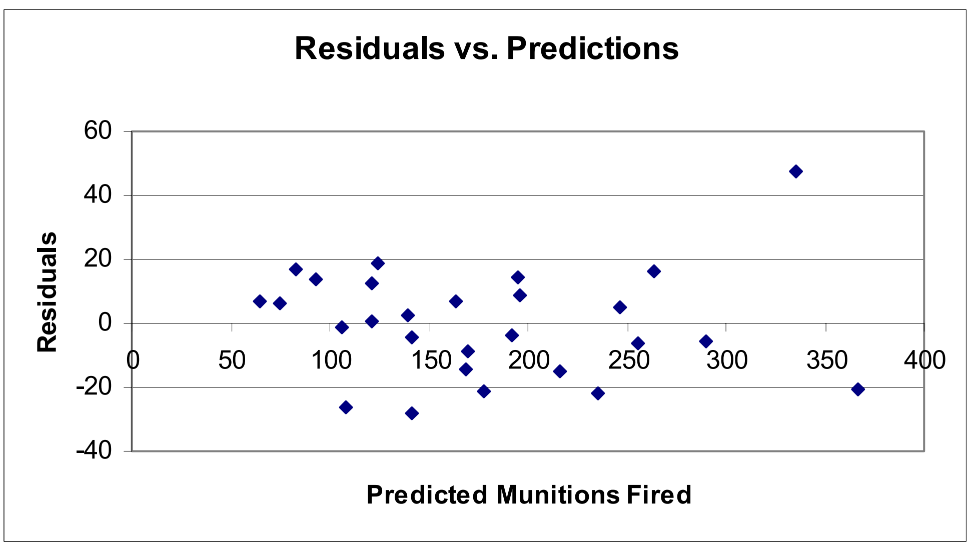


Figure 8: Residuals vs. Predictions of Munitions Fired

Since the polynomial regression model captures the essence of the simulation model output, we can use the regression model to make some general observations about the way timeliness, accuracy, and completeness behave in this simulation. All terms in the regression model are significant at the 0.1% level except for the $[\text{accuracy}]^2$ term, which has a p-value of 37%. This indicates that the effect of accuracy on the response is essentially linear under our coding scheme, and the quadratic term could be removed from the model.

However, the effects of timeliness and completeness are not linear. First, consider what happens to the MOE when all factors are set at their medium level (coded setting of 0) and then timeliness alone is varied. If timeliness is increased to its high level (coded setting of 1) the number of munitions goes down by 71.5 (-37.5 – 34) munitions. But if the level of timeliness is decreased to its low level (coded setting of –1) the number of munitions goes up by only 3.5 (37.5 – 34) munitions. This is clearly not linear behavior and having the squared term in the regression model captures this dynamic. The bigger resulting change from the medium setting is in the direction of *decreasing* the number of munitions fired in spite of the fact that going from the middle level to the high level (30 second to 10 second delay) is a shorter step than going from the middle level to the low level (30 second to 60 second delay).

The same procedure can be applied to the completeness factor. If completeness is increased to its high level (coded setting of 1) the number of munitions goes down by 51.2 (-61.2 + 10.0) munitions. But if the level of completeness is decreased to its low level (coded setting of –1) the number of munitions goes up by 71.2 (61.2 + 10.0). The bigger change from the medium level setting is in the direction of *increasing* the number of munitions fired despite the fact that going from the middle level to the low level (200m grid to 100m grid) is a shorter step than going from the middle level to the high level (200m grid to 400m grid).

The coefficients on the interaction terms in the equation are positive (see Table 3). This means that when both terms are at high levels (+1, +1) the interaction term will be positive and penalize the number of munitions used. The regression model also indicates there exists a beneficial timeliness:accuracy interaction when each of these factors is set at its high level. Figure 9 demonstrates that the model's top three predictions all occur when the (coded) timeliness and accuracy are both equal to +1.

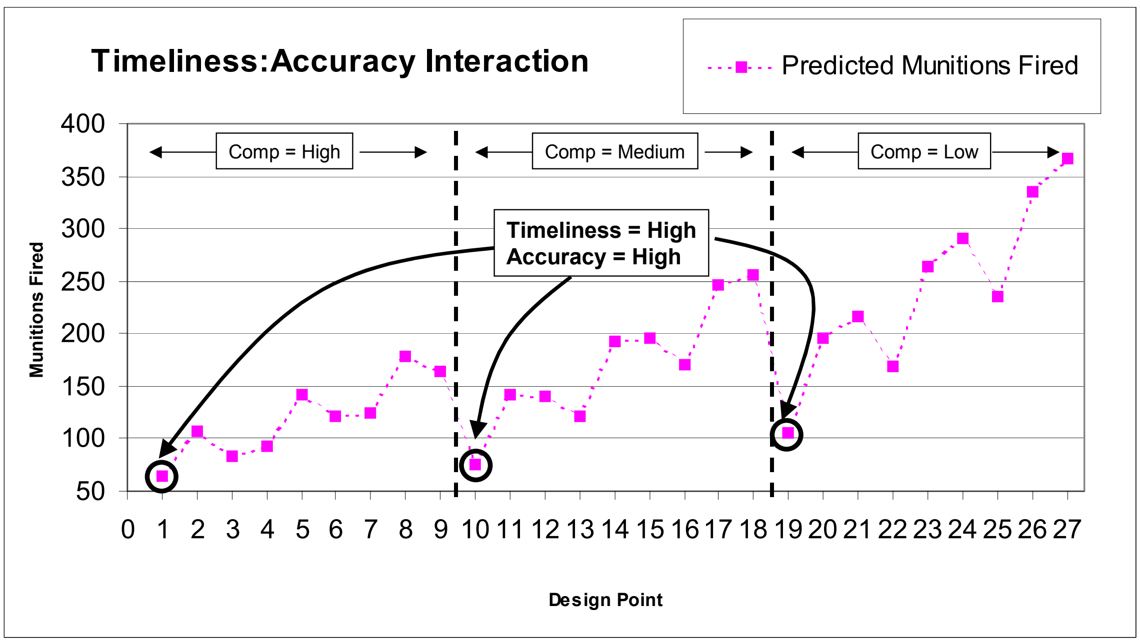


Figure 9: Regression Model Top Predictions

A beneficial timeliness:accuracy interaction is further evidenced by the fact that three of the top five MOE values resulting from the actual simulation runs (refer back to Table 2) are at design points 1, 10, and 19, where timeliness and accuracy are each at their high level. Therefore, while at their high levels, the interaction of timeliness and accuracy obscures the contribution of completeness.

Recall that our regression model accounts for R^2 = 73% of the variability in the MCSKM output. The regression coefficients are uncorrelated in a factorial experiment like this one. Therefore, we can apportion the R^2 value into its component parts: the square of the correlation between munitions and each term in the regression model is that term's contribution to the total R^2. Figure 10 summarizes the results.

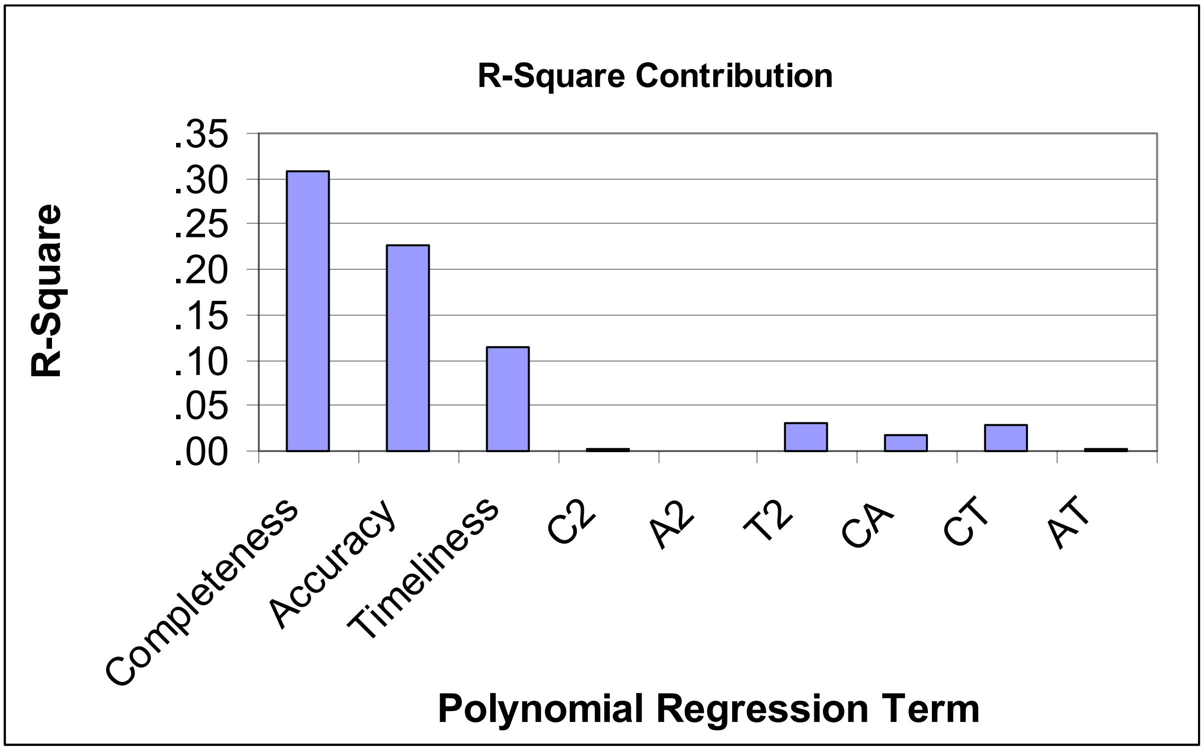


Figure 10: Regression Term R-Square Contribution Chart

The term that single-handedly explains the most variability in the number of munitions fired is completeness at 42%. Accuracy and timeliness follow at 31% and

16% respectively. [Timeliness]^2 as well as the two interactions of completeness:accuracy and completeness:timeliness explain roughly 2-4% of the variability each.

Summary

Our analysis of the MCSKM output shows several things. First, all three factors of timeliness, accuracy and completeness are significant. In other words, each factor has a unique impact on the number of munitions fired—no two factors are interchangeable. Second, all three factors showed up in at least one significant interaction. This means their effects should be evaluated simultaneously, since knowledge of one factor alone will not provide the full picture of the factor's contribution.

Building a complete second order regression model that fits the MCSKM output reasonably well provided a framework to look at the relative significance of the information component terms. The coefficients on the squared terms provided an indication of the linearity of the three factors. The size of the coefficient on the squared term provides an indication of the degree of non-linearity that exists with regards to that factor. The sign of the coefficient is an indicator of which direction of travel from the medium setting provides the bigger change in the number of munitions. A positive sign on the coefficient of the squared term indicates that the number of rounds changes more as the level of the main factor goes down. A negative sign on the coefficient of the squared term indicates that the number of rounds changes more as the level of the main factor goes up.

Finally, with a designed experiment we were able to allocate the explanatory power of the regression model to the individual terms. This gave a good indication regarding the impact of each term's influence on the number of munitions fired.

CONCLUSIONS

The goal of this paper was to present a model and analysis approach that allow us to begin drawing conclusions about how the individual components of information quality can influence combat outcomes. By varying the levels of information timeliness, accuracy and completeness, we found that each information component has a distinctive and significant impact on combat outcomes. Although the output of the MCSKM is heavily dependent upon the scenario's environment, the measure of effectiveness, and input data, we discovered that that the individual effect of timeliness, accuracy and completeness may not be linear. Knowing where and how to achieve an accelerated return based on an incremental change to any of these components is important. We also discovered in this analysis that there are significant synergistic effects that take place between information components. Knowing that the combined effects of two components can overshadow the effect of the remaining component is important as well.

The dynamic relationship among information quality components that emerged from this analysis is likely to exist in virtually any combat scenario and the particulars of that relationship will be unique to that scenario. Such knowledge could assist a concept developer in making wise choices about what technologies and tactics are needed to improve the success of units optimized for specific missions.

While this work lays the groundwork for modeling and analyzing information quality in the Objective Force, further research in several areas is needed to develop a broader understanding of the impact of information on combat outcomes. We now describe a few logical ways to proceed.

First, other constructs of the information quality components are possible. There are other variables that could be associated with each component. Choosing these variables, as well as the appropriate levels for each, and then relating them the proper way would improve the quality of the response and provide further insights into the dynamics of how these information quality components relate to each other.

Second, the MCSKM is adaptable to explore many other scenarios and a broader investigation of the impact of information quality could be undertaken. This can be done by modifying the objective area size and shape, number of UAVs used, distributions used for the varying parameters, number and types of targets, and input values for parameters. Scenarios could be compared with one another to make observations about how the relationship among timeliness, accuracy and completeness may differ. Modifying the MCSKM to allow for multiple types of UAVs would facilitate the exploration of a wider variety of scenarios and provide interoperability with existing and future sensor mix optimization models.

Finally, recall that information can be broken down into two attributes: value and quality. The focus of this paper was on information quality in terms of timeliness, accuracy and completeness. A study on the *value* of information would provide additional insights into how information affects combat outcomes and, combined with this study, provide a more consummate interpretation of the overall impact of information.

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